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BORON/ALUMINUM - GRAPHITE/RESIN ADVANCED FIBER COMPOSITE HYBRIDS

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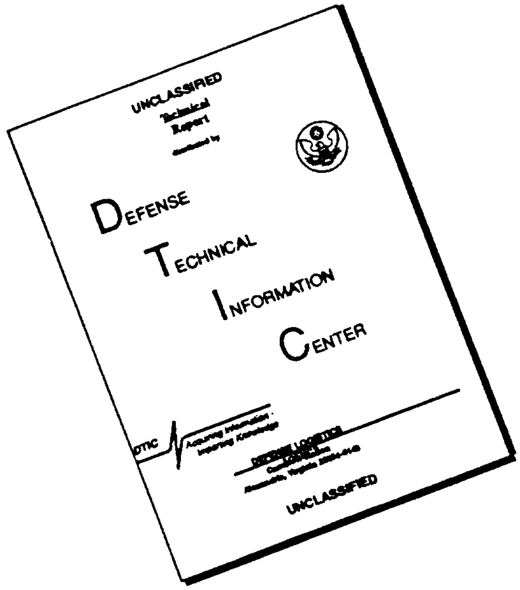

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16. Abstract

An investigation was conducted to determine the fabrication feasibility and to assess the potential of an adhesively bonded metal and resin matrix fiber-composite hybrid as an advanced material for aerospace and other structural applications. The results of fabrication studies and of the evaluation of physical and mechanical properties show that using this hybrid concept makes possible a composite design which, when compared with nonhybrid composites, has greater transverse strength, transverse stiffness, and impact resistance with only a small penalty on density and longitudinal properties. The results also show that laminate theory is suitable for predicting the structural response of such hybrids. The sequence of fracture modes indicates that these types of hybrids can be readily designed to meet fail-safe requirements.

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BORON/ALUMINUM - GRAPHITE/RESIN ADVANCED FIBER COMPOSITE HYBRIDS*

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SUMMARY

An investigation was conducted to determine the fabrication feasibility and to assess the potential of adhesively bonded metal and resin matrix fiber composite hybrids as an advanced material for aerospace and other structural applications. Unidirectional fiber composites made from graphite-fiber/epoxy and boron-fiber/aluminum with a few strategically located titanium foil layers were adhesively bonded to form a combined metal and resin matrix fiber composite hybrid.

Laminates were made using various combinations of these composite systems. Specimens from these laminates were tested to determine tensile, flexure, Izod impact, and notch properties. Laminate analysis was used to calculate the lamination residual stresses throughout the hybrids. The results obtained are compared with those of unidirectional materials and are discussed with respect to impact resistance, notch sensitivity, transverse strength, and ease of fabrication.

The investigation showed that hybrid composites of the type described can readily be fabricated, and metallographic examinations indicated them to be of good quality.

The evaluation of physical and mechanical properties show that with this hybrid concept it is possible to design a composite which, when compared with nonhybrid composites, has greater transverse strength, transverse stiffness, and impact resistance. The results also show that laminate theory is suitable for predicting the structural response of such hybrids. The sequence of fracture modes indicates that these types of hybrids can be readily designed to meet fail-safe requirements.

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INTRODUCTION

Advanced fiber/resin and fiber/metal matrix composites are used most efficiently when the fiber and load directions are coincident. To provide strength or stiffness in more than one direction, composites with fibers oriented in several directions are necessary. Orienting fibers in more than one direction in the same composite, however, reduces their efficiency and can introduce lamination residual stresses comparable to the transverse and shear strength properties of the unidirectional composite. These lamination residual stresses may limit the resistance to mechanical loads of composite components. In particular, it may reduce their resistance to thermal or mechanical cyclic load. In addition, commercially available graphite-fiber/resin and boron-fiber/aluminum composites are inherently weak in impact and erosion resistance.

The aforementioned difficulties may be overcome to a significant extent by using the best characteristics of the resin matrix composite, the metal matrix composite, and foil materials combined in a hybrid composite. Metal and resin matrix fiber composite hybrids discussed in this report are adhesively bonded unidirectional composites made from graphite-fiber/epoxy and boron-fiber/aluminum and a few strategically located titanium foil layers (see schematic, fig. 1). The addition of the titanium layers improves the laminate transverse properties and eliminates the need for angleplying.

This report describes the adhesively bonded metal and resin matrix fiber composite hybrid concept and reports some experimental and theoretical results that indicate its potential. Laminates for this investigation were made using various combinations of the above composite systems. Specimens from these laminates were subjected to tension, flexure, thin specimen Izod impact, and notch-sensitivity tests. Laminate analysis was used to calculate the lamination residual stresses throughout the hybrids. The results obtained are compared with those of metals and unidirectional composites and are discussed with respect to impact resistance, notch sensitivity, transverse strength, and ease of fabrication.

The fabrication process, composite configurations, specimen preparation, test methods, and method of analysis are described. Comparisons with other composites are reported. Unique applications of the metal and resin matrix hybrid composites to aerospace structures are identified.

To have useful qualitative and quantitative comparisons of the results of the several laminates tested in this investigation, the geometry of the test specimens was kept similar.

DESCRIPTION OF COMPOSITE SYSTEMS

In the following section the various types of laminates investigated are discussed.

Constituent Plies and Materials

Five types of laminates were made. The types of laminates, laminate designations, constituent materials, and material suppliers are listed in table I(a). The laminate configurations are shown in table I(b).

Thermal, physical and mechanical properties of the constituent materials are summarized in table II.

Laminate Fabrication

Type I. - Twelve unidirectional plies of A-S/3501 graphite prepreg tape were assembled and cured in a metal mold using the standard curing conditions recommended by Hercules, Inc., for this type of epoxy resin system (3 hr at 149° C (300° F) and 69 N/cm^2 (100 psi)).

Type II. - Eight unidirectional plies of B/Al were diffusion bonded by the manufacturer, Amercom, Inc. The diffusion bonding conditions consisted of 3100 newtons per square centimeter (4500 psi) pressure at 510° C (950° F) for 1/2 hour.

Type III. - Seven unidirectional plies of B/Al were adhesively bonded using FM 1000 structural adhesive. Before bonding each B/Al ply was treated with a 10-percent sodium dichromate solution at room temperature for 5 minutes. Each ply was rinsed in water and methyl alcohol, then dried. During the bonding operation, a pressure of 415 newtons per square centimeter (600 psi), a temperature of 190° C (375° F), and a time of 1 hour were used to cure the adhesive.

Type IV. - Five sheets of titanium foil and six unidirectional plies of B/Al were adhesively bonded using FM 1000 structural adhesive. The foil was laid up so that its primary rolling direction was parallel to the fiber direction. Before bonding, the titanium foil plies were degreased and treated with a 5-percent hydrogen fluoride solution for 30 seconds at room temperature. This was followed by a water and methyl alcohol rinse and then by drying. The prebonding treatment of the B/Al and the time-pressure-temperature cycle for curing was identical to that used for the type III laminates.

Type V. - Five sheets of titanium foil, two plies of B/Al, and six plies of graphite/epoxy were adhesively bonded. The titanium and B/Al plies received the same treatment before bonding as the type IV laminates. The FM 1000 adhesive was used for all of the metal-to-metal and metal-to-graphite interface bonds. The graphite/epoxy plies were

bonded using the 3501 matrix resin. The time-pressure-temperature cycle was selected to initially cure the graphite/epoxy plies and then effect bonding at the FM 1000 interfaces. The procedure was as follows: After assembling the various components of the laminate in a metal mold, a thermocouple was placed in contact with the edge of the composite. A Wabash laminating press was then preheated to 135° C (275° F). The cold mold was placed in the press and 10 newtons per square centimeter (15 psig) contact pressure was initiated. When the thermocouple reached 38° C (100° F), contact pressure was maintained for 16 minutes. A pressure of 415 newtons per square centimeter (600 psig) was applied and a temperature of 135° C (275° F) was maintained for another 14 minutes to complete gelation of the epoxy matrix resin. After this, the press temperature was increased to 150° C (300° F) and pressure was maintained for 30 minutes to advance the cure of the epoxy. Then the press temperature was increased to 175° C (350° F), and the pressure was maintained for 120 minutes to complete the cure of the epoxy and the adhesive. The press heaters were turned off and the laminate was permitted to cool under pressure to room temperature.

Typical cross sections of the laminates are shown in the photomicrographs of figure 2. The materials and various plies in these laminates are also indicated in this figure. The detailed arrangement of the materials, plies and their corresponding thicknesses are given in table I(b).

DESCRIPTION OF TEST PROGRAM

In this section the specimen preparation, instrumentation, types of tests, and procedures are described.

Specimen Preparation

Unidirectional laminates ranging from 0.13 to 0.15 centimeter (0.05 to 0.06 in.) thick were cut into 1.27-centimeter (0.500-in.) wide specimens by using a precision wafer cutting machine equipped with a diamond cutting wheel. A specimen layout plan is shown in figure 3.

To determine the notch sensitivity of the laminates, through-the-thickness center slots were placed in specimens using electrical discharge machining. All notched specimens were machined this way except for the type I transverse specimen. This specimen was double edge notched using a 0.013-centimeter (0.005-in.) wide cutting wheel. In all cases the notch root radius was 0.008 centimeter (0.003 in.) or less. A single slot length, 0.043 centimeter (0.017 in.), was used for tests on laminates I, II, and V. Two

slot lengths, 0.025 and 0.043 centimeter (0.010 and 0.017 in.), were used for tests on laminates III and IV.

Where required, the specimen ends were reinforced with adhesively bonded aluminum or fiber glass tabs. The ends of all specimens used to determine longitudinal smooth tensile properties were reinforced. And the ends of all type I specimens that were subjected to tensile loadings were reinforced.

Specimen Instrumentation

The specimens used to determine smooth tensile properties were instrumented with strain gages to measure longitudinal and transverse strain.

Types of Tests and Procedures

Composite density. - Samples of each of the five types of laminates were evaluated for density by using the ASTM D-792 test method for "Specific Gravity and Density of Plastics by Displacement."

Smooth and notch tensile strengths. - The smooth and notch tensile specimens were loaded to failure using a hydraulically actuated universal testing machine. Longitudinal specimens had a test section that was about 7.6 centimeters (3 in.) long, and the transverse specimens had a test section that was about 5 centimeters (2 in.) long. The notched specimens were loaded to failure, and the maximum load noted. Loading was halted at convenient intervals when testing the smooth specimens so that strain gage data (using a digital strain recorder) could be obtained.

Flexural strengths. - Test specimens having a length of 7.6 centimeters (3 in.) were tested for flexural strength in an Instron testing machine. A three-point loading system was used with a span of 5.1 centimeters (2 in.).

Izod impact strengths. - Unnotched specimens were subjected to Izod impact strength tests using a TMI impact tester equipped with a 0.9-kilogram (2-lb) hammer. The velocity of the hammer was 3.35 meters per second (11 ft/sec).

EXPERIMENTAL TEST PROGRAM RESULTS

In this section results obtained for density, tensile smooth and notched, flexural, and Izod impact tests are summarized and discussed.

Density

The measured densities of the laminates tested are given in the first column of table III(a). Note that the density of laminate V (Ti, B/Al, Gr/Ep) is the same as that of E-glass/epoxy, 2.08 grams per cubic centimeter (0.074 lb/in.^{3}).

Smooth Tensile Tests

Table III(a) summarizes the test data obtained from smooth specimens (specimens without slots). This table includes laminate longitudinal (load applied parallel to fibers) and transverse (load applied normal to fibers) tensile properties. The initial tangent moduli and Poisson's ratios are given. As can be seen, inclusion of titanium foil layers in the hybrids improves the transverse strength properties relative to the unidirectional material. The longitudinal and transverse fracture strains of the two hybrids are approximately equal.

A comparison of the results of the diffusion-bonded and adhesively bonded B/Al laminates shows that these laminates have approximately the same properties except for the longitudinal fracture stress. The longitudinal fracture stress of the adhesively bonded laminate is about 70 percent of that of the diffusion bonded laminate.

Stress-strain curves for all the types of laminates are shown in figure 4(a) for loads parallel to fibers and in figure 4(b) for loads transverse to the fibers. The stress-strain curves are linear to fracture, or nearly so, for specimens loaded parallel to the fibers. However, specimens loaded transverse to the fibers exhibit considerable nonlinearity (fig. 4(b)). Curves of Poisson's strain versus axial strain are shown in figure 5.

One interesting result was the failure mode of laminate V (Ti, B/Al, Gr/Ep) tested in longitudinal tension. The boron/aluminum plies failed when the tensile stress produced strain about equal to the fracture strains of the boron fibers. The Gr/Ep plies remained intact and were therefore still capable of carrying mechanical load. The authors believe this failure mode to be significant because these hybrids can be designed to have inherent fail-safe design characteristics.

Notch Tensile Tests

The test data obtained from slotted specimens are summarized in table III(b). Two interesting points to be observed from the data in table III(b) are

(1) The notch effects are small and about the same for both the longitudinal and transverse directions in the hybrid composites.

(2) Notch strengthening for the transverse tensile specimens was observed in both the diffusion bonded and adhesively bonded B/Al laminates. This strengthening may be attributed, in part, to the transverse restraining effects of the fibers at the slot ends.

Flexural Tests

The test data obtained from subjecting test specimens to three-point flexural loading are summarized in table III(c). The important points to be observed from the data are

(1) The hybrid composites exhibit significant improvement in transverse strength compared with other composites.

(2) The hybrid composites exhibit a decrease in the longitudinal flexural strength compared with other composites.

(3) The hybrid composite flexural longitudinal modulus is slightly less than that of the adhesively bonded B/Al composite.

(4) The transverse modulus of the Ti, B/Al, Gr/Ep hybrid composite is about four times greater than that of the Gr/Ep composite.

Impact Tests

Data obtained by subjecting the thin composite specimens to unnotched Izod impact tests are summarized in table IV. In table IV the impact strengths of some other composites and materials are given for comparison. To make the comparison, the Izod impact data were normalized with respect to the cross sectional area of the composite. In table IV the low and high Izod impact strengths and the number of specimens for each composite or material are given.

The important point to be observed from the data in table IV is the following: Using the metal and resin matrix hybrid composite concept, composite materials may be designed with Izod impact resistance approaching that of aluminum. In addition, when the Izod impact values are normalized with respect to density, the longitudinal impact resistance of the type V hybrid is about 60 percent of that of the titanium.

THEORETICAL PROGRAM RESULTS

In this section the calculation method used and results obtained for laminate densities, elastic properties, plate stiffnesses, and lamination residual stresses are described.

Density and Elastic Properties

Laminate analysis was used to assess the applicability of linear laminate analysis to hybrid composites. For this purpose the laminate analysis available in the Multilayer Fiber Composite Analysis Computer Code (ref. 1) was used. The inputs for the analysis of the metal and resin matrix hybrid composites consisted of the ply constituent properties data in table II and the ply arrangement and thicknesses data in table I(b).

The output of the computer code consists of the following:

(1) Composite density

(2) Longitudinal, transverse, and shear moduli

(3) Major and minor Poisson's ratios

(4) Plate bending stiffnesses, a measure of the structural response of the laminate.

The flexural longitudinal and transverse moduli are obtained from the plate bending stiffnesses using the following equations:

$$E_{FL} = \frac{12}{t^3}\left(D_{11} - \frac{D_{12}^2}{D_{22}}\right) \tag{1}$$

$$E_{FT} = \frac{12}{t^3}\left(D_{22} - \frac{D_{12}^2}{D_{11}}\right) \tag{2}$$

where E denotes modulus, the subscript F flexural, L longitudinal and T transverse; the D's denote plate bending stiffnesses with the subscript 1 denoting measurements taken along the fiber direction and 2 transverse to it; and t denotes the laminate thickness.

The results of the computer code laminate analysis are summarized in table V. In this table the flexural moduli predicted by equations (1) and (2) are given. Also, corresponding values for aluminum and titanium are included for comparison. As can be seen from these data, unidirectional hybrid composites can be designed with torsional stiffness equal to that of aluminum.

No attempt was made to predict fracture stresses (strains) of the hybrids in the present investigation. But, if the fracture strains in both longitudinal and transverse directions are approximately the same and about equal to the yield strain of the titanium or fracture strain of the boron fibers (see table III(a)), prediction of hybrid fracture strain

should be rather straightforward. Additional experimental data are needed to place the above observation on a firmer basis.

It is also noted that no attempt was made to determine stress intensity factors of the notched composites and hybrids. Since the hybrid composites exhibited small notch-sensitivity, the stress intensity factor for such hybrids might not even be needed.

Lamination Residual Stresses

Lamination residual stresses are induced in the constituent material layers of the metal and resin matrix composites because of

(1) The mismatch of the thermal coefficient of expansions

(2) The temperature difference between the cure and room temperatures.

The lamination residual stresses were computed using laminate analysis as is described in reference 2. The results are summarized in table VI.

Comparing lamination residual stresses from table VI with corresponding fracture (yield) stresses in table II shows that the lamination residual stresses are relatively low. For example, those in the adhesive are less than 50 percent of the corresponding fracture stresses. Since the adhesive has relatively low stiffness compared with the other constituents, the hybrid can be subjected to considerable mechanical load before the adhesive will reach its fracture stress.

Tests to determine the thermal fatigue resistance of these hybrid composites showed that no degradation took place when samples were cycled between -73° and 150° C (-100° and 300° F) for 1000 cycles.

Comparisons of Predicted and Measured Data

Comparing corresponding values from tables III(a) and V shows that the laminate theory predicts densities, moduli, and Poisson's ratios which are in good agreement with initial measured data. No measured data were obtained for shear modulus nor (measured directly) for plate-type bending stiffnesses.

A comparison of the corresponding values from tables III(c) and V shows that linear laminate theory predicts flexural longitudinal moduli that are in very good agreement with measured data. The comparison for flexural transverse moduli is fair with the predicted values higher than the measured. This is to be expected since transverse flexural loading strains the specimen nonlinearly as shown in figure 4(b).

The important point from these comparisons is that laminate theory appears to be suitable for predicting the structural response of the metal matrix and resin matrix fiber composite hybrids. And from what has been discussed previously, laminate theory is

expected to be applicable for predicting the strength of these hybrids based on constituent plies and materials fracture data.

GENERAL COMMENTS

Several important observations may be made based on the results of this investigation.

First, adhesive bonding is a feasible method for producing high quality composites. Combining resin matrix composites with metal matrix composites and titanium foil produces hybrid composites with improved impact and transverse properties. The approach used in this investigation permits both resin and metal matrix composites to be used in a unidirectional configuration, which simplifies the fabrication process.

Second, this type of hybrid composite with titanium layers for faces has distinct advantages over other advanced composites where erosion and impact resistance control the design. This type of hybrid is also more suitable for joints since the titanium layers increase the local bearing strength. Optimum combinations of metal matrix composites, resin matrix composites, and titanium layers may meet a multitude of difficult design requirements while maintaining fabrication simplicity and low lamination residual stresses.

Finally, the fracture path or fracture surface exhibited by the hybrids tested appeared to be well defined compared with advanced composites in general. These well defined fracture paths are illustrated in the photographs of fractured specimens shown in figure 6. As can be seen, the fracture paths are virtually straight lines. It is believed that the titanium layers contribute to the straightness of the paths. The importance of this feature is that fracture is controlled by one simple mode as compared with the several modes typical in advanced composites. Thus it is relatively easy to postulate fracture hypotheses and subsequently verify them by test.

CONCLUSIONS

The results of an investigation to determine the fabrication feasibility and to evaluate the potential of adhesively bonded metal matrix and resin matrix fiber composite hybrids lead to the following conclusions:

1. High quality hybrid composites can be fabricated by adhesive bonding.

2. Mechanical tests of adhesively bonded composite hybrids showed that it is possible to make a composite with the following desirable properties:

   a. Longitudinal strength and stiffness approaching corresponding properties of other advanced fiber composites

b. Transverse flexural strength approaching that of the yield strength of the titanium alloy

c. Longitudinal impact resistance approaching that of aluminum

d. Transverse and shear stiffnesses comparable to those of 6061 aluminum

e. Density comparable to that of commercially available E-glass/epoxy composites

3. The judicious location of the titanium-foil layers in the laminates may result in predictable high-energy absorption failure modes for these hybrids. Along the fiber direction fracture is governed by the fiber fracture strain. Transverse to the fiber direction and in shear, fracture appeared to be governed by the yield strain of the titanium foils.

4. The lamination residual stresses in the adhesive are about 50 percent of the corresponding failure stress of the adhesive; therefore, significant capacity remains for carrying mechanical load in the hybrid composites.

5. The Ti, B/Al, Gr/Ep hybrid exhibited a primary fracture wherein the B/Al plies failed leaving the Gr/Ep plies intact. The occurrence of this failure sequence might be used as a basis for design of fail-safe structural components.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 7, 1974,
506-17.

REFERENCES

1. Chamis, Christos C.: Computer Code for the Analysis of Multilayered Fiber Composites - User's Manual. NASA TN D-7013, 1971.

2. Chamis, Christos C.: Lamination Residual Stresses in Multilayered Fiber Composites. NASA TN D-6146, 1971.

TABLE I. - LAMINATE DESCRIPTIONS

(a) Layer materials and source

Laminate		Materials	Source
Type	Composition		
I	Gr/Ep	Unidirectional type A-S graphite fibers with type 3501 epoxy resin in the form of 7.6-cm (3-in.) wide prepreg tape	Hercules, Inc.
II	B/Al	Diffusion-bonded unidirectional layers of 0.014-cm (5.6-mil) diam boron fibers in a 6061 aluminum alloy matrix	Amercom, Inc.
III	B/Al	Monotape layers of 0.014-cm (5.6-mil) diam boron fibers in a 6061 aluminum alloy matrix	Amercom, Inc.
		Plies from the monotape were adhesively bonded using FM 1000 structural adhesive in film form	American Cyanamid Co.
IV	Ti, B/Al (hybrid)	Titanium (6Al-4V) foil, 0.0038-cm (0.0015-in.) thick as rolled	Teledyne Rodney Metals
		Individual monotape layers of 0.014-cm (5.6-mil) diam boron fibers in a 6061 aluminum alloy matrix	Amercom, Inc.
		FM 1000 structural adhesive in film form	American Cyanamid Co.
V	Ti, B/Al, Gr/Ep (hybrid)	Titanium foil (6Al-4V), 0.0038-cm (0.0015-in.) thick	Teledyne Rodney Metals
		Individual monotape layers of 0.014-cm (5.6-mil) diam boron fibers in a 6061 aluminum alloy	Amercom, Inc.
		Type A-S graphite/3501 prepreg	Hercules, Inc.
		FM 1000 structural adhesive in film form	American Cyanamid Co.

TABLE I. - Concluded. LAMINATE DESCRIPTION

(b) Laminate

Laminate type	Layer number	Material[a]	Layer thickness, t, cm	Layer thickness, t, in.
I	1	Gr/Ep	0.0118	0.0049
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
	11			
	12			
			0.1416	0.0588
II	1	B/Al	0.0166	0.0069
	2			
	3			
	4			
	5			
	6			
	7			
	8			
			0.1328	0.0552
III	1	B/Al	0.0178	0.0074
	2	FM 1000	.0007	.0003
	3	B/Al	.0178	.0074
	4	FM 1000	.0007	.0003
	5	B/Al	.0178	.0074
	6	FM 1000	.0007	.0003
	7	B/Al	.0178	.0074
	8	FM 1000	.0007	.0003
	9	B/Al	.0178	.0074
	10	FM 1000	.0007	.0003
	11	B/Al	.0178	.0074
	12	FM 1000	.0007	.0003
	13	B/Al	.0178	.0074
			0.1281	0.0536
IV	1	Ti	0.0036	0.0015
	2	FM 1000	.0002	.0001
	3	Ti	.0036	.0015
	4	FM 1000	.0002	.0001
	5	B/Al	.0178	.0074
	6	FM 1000	.0002	.0001
	7	B/Al	.0178	.0074
	8	FM 1000	.0002	.0001
	9	B/Al	.0178	.0074
	10	FM 1000	.0002	.0001
	11	Ti	.0036	.0015
	12	FM 1000	.0002	.0001
	13	B/Al	.0178	.0074
	14	FM 1000	.0002	.0001
	15	B/Al	.0178	.0074
	16	FM 1000	.0002	.0001
	17	B/Al	.0178	.0074
	18	FM 1000	.0002	.0001
	19	Ti	.0036	.0015
	20	FM 1000	.0002	.0001
	21	Ti	.0036	.0015
			0.1268	0.0529
V	1	Ti	0.0036	0.0015
	2	FM 1000	.0017	.0007
	3	Ti	.0036	.0015
	4	FM 1000	.0017	.0007
	5	B/Al	.0178	.0074
	6	FM 1000	.0017	.0007
	7	Gr/Ep	.0120	.0050
	8	Gr/Ep	.0120	.0050
	9	Gr/Ep	.0120	.0050
	10	FM 1000	.0017	.0007
	11	Ti	.0036	.0015
	12	FM 1000	.0017	.0007
	13	Gr/Ep	.0120	.0050
	14	Gr/Ep	.0120	.0050
	15	Gr/Ep	.0120	.0050
	16	FM 1000	.0017	.0007
	17	B/Al	.0178	.0074
	18	FM 1000	.0017	.0007
	19	Ti	.0036	.0015
	20	FM 1000	.0017	.0007
	21	Ti	.0036	.0015
			0.1392	0.0579

[a]See part (a).

TABLE II. - PROPERTIES OF CONSTITUENTS USED TO MAKE HYBRID COMPOSITES (FROM MATERIAL SUPPLIERS)

Property	Ti (6Al-4V)	Adhesive (FM 1000)	B/Al (5.6/6061)	Gr/Ep (A-S/3501)
Density, g/cm^3 ($lb/in.^3$)	4.43 (0.16)	1.16 (0.042)	2.63 (0.095)	1.58 (0.057)
Nominal thickness, cm (in.)	0.0038 (0.0015)	0.0013 (0.0005)	0.0180 (0.0070)	0.0130 (0.0050)
Approximate fiber volume, percent	----------------	----------------	50	60
[a]Modulus, N/cm^2 (ksi):				
E_1	11.0×10^6 (16.0×10^3)	0.14×10^6 (0.20×10^3)	23.3×10^6 (33.8×10^3)	12.8×10^6 (18.5×10^3)
E_2	11.0×10^6 (16.0×10^3)	0.14×10^6 (0.20×10^3)	14.5×10^6 (21.0×10^3)	1.4×10^6 (2.0×10^3)
G_{12}	4.3×10^6 (6.2×10^3)	0.05×10^6 (0.07×10^3)	5.0×10^6 (7.2×10^3)	0.42×10^6 (0.61×10^3)
G_{23}	4.3×10^6 (6.2×10^3)	0.05×10^6 (0.07×10^3)	4.7×10^6 (6.8×10^3)	0.25×10^6 (0.37×10^3)
Poisson's ratio:				
ν_{12}	0.30	0.40	0.25	0.25
ν_{23}	0.30	0.40	0.39	0.47
Coefficient of thermal expansion, cm/cm/°C (in./in./°F):				
α_1	3.2×10^{-6} (5.8×10^{-6})	22.2×10^{-6} (40.0×10^{-6})	1.8×10^{-6} (3.3×10^{-6})	0.18×10^{-6} (0.33×10^{-6})
α_2	3.2×10^{-6} (5.8×10^{-6})	22.2×10^{-6} (40.0×10^{-6})	5.9×10^{-6} (10.7×10^{-6})	9.0×10^{-6} (16.2×10^{-6})
Fracture stress, N/cm^2 (ksi):				
S_{1T}	[b]83×10^3 (120)	[c]4×10^3 (6)	152×10^3 (220)	125×10^3 (181)
S_{1C}	[b]83×10^3 (120)	[c]7×10^3 (10)	172×10^3 (250)	114×10^3 (165)
S_{2T}	[b]83×10^3 (120)	[c]4×10^3 (6)	14×10^3 (20)	6×10^3 (8)
S_{2C}	[b]83×10^3 (120)	[c]7×10^3 (10)	17×10^3 (25)	17×10^3 (25)
S_s	48×10^3 (70)	5×10^3 (7)	16×10^3 (23)	9×10^3 (13)

[a]Subscript notation: 1 - along fiber direction, 2 - transverse to fiber, 3 - through the thickness, T - tension, C - compression, and S - shear.

[b]0.2 Percent offset yield strength.

[c]Estimated value.

TABLE III. - PROPERTIES OF TENSILE SPECIMENS

(a) Smooth specimens

Laminate type	Density		Fracture strength				Fracture strain, percent		Initial modulus of elasticity				Initial Poisson's ratio	
	g/cm^3	lb/in.^{3}	Longitudinal		Transverse		Longi- tudinal	Trans- verse	Longitudinal		Transverse		Longi- tudinal	Trans- verse
			N/cm^2	ksi	N/cm^2	ksi			N/cm^2	ksi	N/cm^2	ksi		
I	1.58	0.057	113×10^3	164	3.9×10^3	5.6	1.02	0.34	10×10^6	15×10^3	1.2×10^6	1.8×10^3	0.33	0.03
II	2.46	.089	157	228	12.2	17.7	.79	.12	22	32	17	25	.24	.14
III	2.52	.091	110	159	16.3	23.7	.67	.21	21	30	16	23	.26	.14
IV	2.71	.098	110	160	30.4	44.1	.68	.88	19	27	14	20	.27	.18
V	2.05	.074	86	125	21.7	31.5	.73	1.01	12	18	5.9	8.5	.25	.11

(b) Notched specimens

Laminate type	Notch length		Net fracture strength				Notch strength ÷ unnotched strength	
	cm	in.	Longitudinal		Transverse		Longitudinal	Transverse
			N/cm^2	ksi	N/cm^2	ksi		
I	0.43	0.17	(a)	(a)	[b]1.5×10^3	[b]2.2	1.00	[b]0.39
II	.43	.17	108×10^3	157	19.0	27.5	.69	1.55
III	.25	.10	98	142	19.2	27.9	.89	1.18
	.43	.17	97	140	15.4	22.4	.88	.95
IV	.25	.10	97	140	26.9	39.0	.87	.88
	.43	.17	92	134	25.2	36.6	.84	.83
V	.43	.17	68	98	16.5	24.0	.78	.76

[a]No notch growth; specimen split parallel to fibers.
[b]Double edge notch specimen.

(c) Flexural specimens

Laminate type	Fracture stress				Modulus[c]			
	Longitudinal		Transverse		Longitudinal		Transverse	
	N/cm^2	ksi	N/cm^2	ksi	N/cm^2	ksi	N/cm^2	ksi
I	170×10^3	246	5.5×10^3	8	14×10^6	20×10^3	1.7×10^6	2.5×10^3
II	210	304	27	39	27	39	9.7	14
III	141	204	32	46	21	31	12	17
IV	141	204	67	97	19	27	12	17
V	128	185	57	83	15	22	7.6	11

[c]The modulus was calculated using chart deflection and a calibration factor to account for Instron compliance. These values are only approximate.

TABLE IV. - SUMMARY OF THIN-SPECIMEN IZOD IMPACT STRENGTH RESULTS AND COMPARISONS WITH SOME OTHER MATERIALS

[Specimen nominal dimensions: 1.27 cm (0.50 in.) wide by 0.15 cm (0.06 in.) thick.]

Material	Test direction	Izod impact strength[b]				Number of specimens
		$(cm-N)/cm^2$		$(in.-lb)/in.^2$		
		Low	High	Low	High	
Laminate I	Longitudinal	569	625	325	357	4
	Transverse	77	84	44	48	2
Laminate II	Longitudinal	485	501	277	286	
	Transverse	401	432	229	247	
Laminate III	Longitudinal	271	378	155	216	
	Transverse	172	278	98	159	4
Laminate IV	Longitudinal	432	443	247	253	2
	Transverse	313	392	179	224	4
Laminate V	Longitudinal	1110	1261	634	720	2
	Transverse	326	354	186	202	
HT-S/PMR-PI[a]	Longitudinal	357	361	204	206	
	Transverse	70	75	40	43	
E-glass/epoxy	-----------	436	447	249	255	3
0.01-cm (4-mil) diam B/6061 Al	Longitudinal	443	476	253	272	2
6061 Al	-----------	1324	1600	756	914	2
Ti(6Al-4V)	-----------	4421	4479	2525	2558	2

[a]PMR-polymerization of monomeric reactants; PI-polyimide.
[b]Impact strength normalized with respect to area.

TABLE V. - SUMMARY OF PREDICTED[a] LINEAR ELASTIC CONSTANTS AND PLATE TYPE BENDING STIFFNESS FOR HYBRID COMPOSITES AND SOME MEASURED METAL VALUES

Material	Density		Modulus						Poisson's ratio	
	g/cm³	lb/in.³	N/cm²			ksi				
			Longitudinal	Transverse	Shear	Longitudinal	Transverse	Shear	Major	Minor
Laminate I	1.58	0.057	12.8×10^6	1.4×10^6	0.42×10^6	18.5×10^3	2.0×10^3	0.61×10^3	0.25	0.027
Laminate II	2.63	.095	22.8	14.5	5.0	33.0	21.0	7.20	.25	.16
Laminate III	2.58	.093	22.0	14.0	4.8	31.9	20.3	6.96	.25	.16
Laminate IV	2.85	.103	20.7	13.7	4.8	30.0	19.9	6.92	.26	.17
Laminate V	2.19	.079	13.9	6.0	2.1	20.2	8.7	3.0	.26	.11
Al (6061)	2.71	.098	6.9	6.9	2.49	10.0	10.0	3.61	.33	.33
Ti (6Al-4V)	4.43	.160	11.0	11.0	4.3	16.0	16.0	6.2	.30	.30

Material	Plate type bending stiffness[b]								Flexural modulus			
	N-cm				lb-in.				N/cm²		ksi	
	D_{11}	D_{12}	D_{22}	D_{33}	D_{11}	D_{12}	D_{22}	D_{33}	Longitudinal	Transverse	Longitudinal	Transverse
Laminate I	3630	98	391	118	316	8.5	34.1	10.3	12.8×10^6	1.4×10^6	18.5×10^3	2.0×10^3
Laminate II	5530	890	3510	1160	482	77.6	306	101	22.8	14.5	33.0	21.0
Laminate III	4930	786	3140	1040	430	68.5	274	90.2	22.0	14.0	31.9	20.3
Laminate IV	4050	746	2840	950	353	65.0	247	82.8	18.7	13.1	27.2	19.0
Laminate V	4120	694	2590	870	359	60.5	226	75.9	14.5	9.2	21.1	13.3
6061 Al	2330	752	2330	746	203	65.5	203	65	6.9	6.9	10.0	10.0
Ti (6Al-4V)	3630	1090	3630	1290	316	95.0	316	112	11.0	11.0	16.0	16.0

[a]Properties predicted by multilayer fiber composite computer code (ref. 1).

[b]Plate-type stiffness for metals were computed from the relation $D_{11} = D_{22} = Et^3/12(1-\nu^2)$ and $D_{33} = Gt^3/12$ where t was taken as 0.15 cm (0.06 in.).

TABLE VI. - COMPUTED LAMINATION RESIDUAL STRESSES IN COMPOSITES

DUE TO COOLING FROM 177° C (350° F) PROCESSING TEMPERATURE

Laminate	Test direction	Layer[a]							
		Ti foil		B/Al		Gr/Ep		Adhesive	
		Residual stress							
		N/cm^2	ksi	N/cm^2	ksi	N/cm^2	ksi	N/cm^2	ksi
I	Longitudinal	---------	-----	---------	----	0	0	-------	---
	Transverse	---------	-----	---------	----	0	0	-------	---
II	Longitudinal	---------	-----	0	0	--------	----	-------	---
	Transverse	---------	-----	0	0	--------	----	-------	---
III	Longitudinal	---------	-----	-0.07×10^3	-0.1	--------	----	2.5×10^3	3.6
	Transverse	---------	-----	-.07	-.1	--------	----	2.1	3.1
IV	Longitudinal	3.9×10^3	5.6	-.7	-1.0	--------	----	2.5	3.6
	Transverse	-13.3	-19.3	2.2	3.2	--------	----	2.1	3.1
V	Longitudinal	8.3	12.1	8.1	11.7	-6.5×10^3	-9.5	2.5	3.6
	Transverse	-13.5	-19.6	1.7	2.4	2.1	3.1	2.2	3.2

[a]See table I.

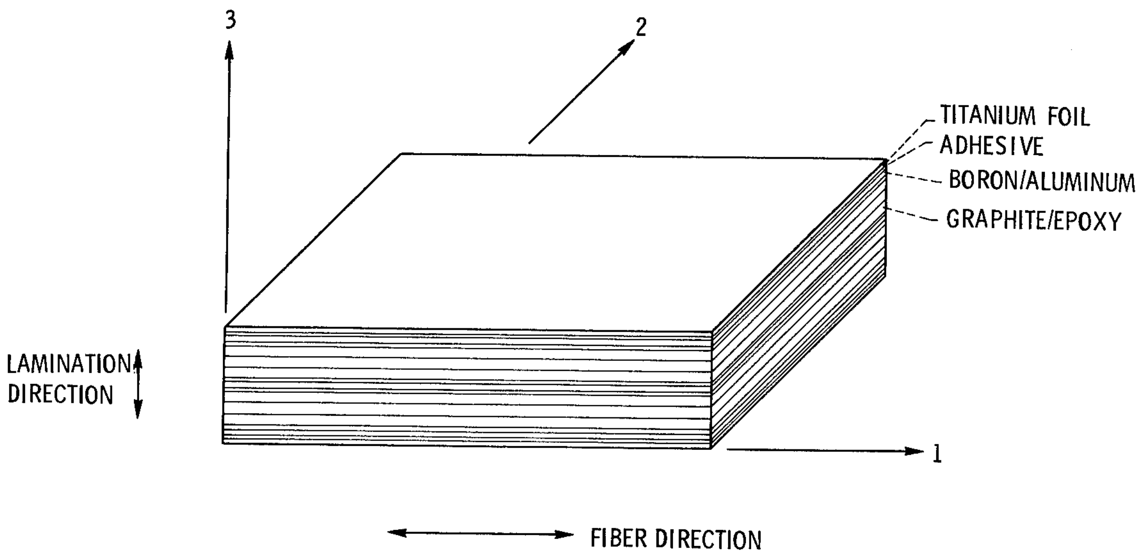
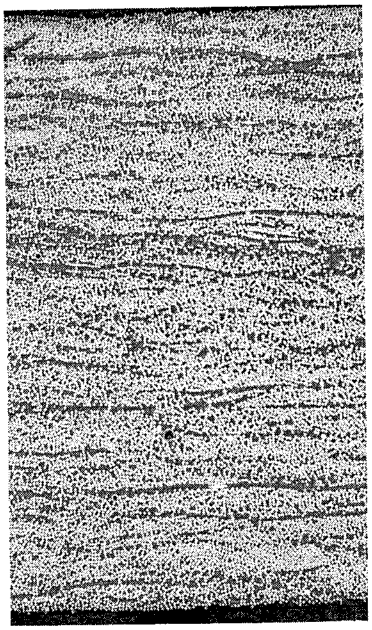
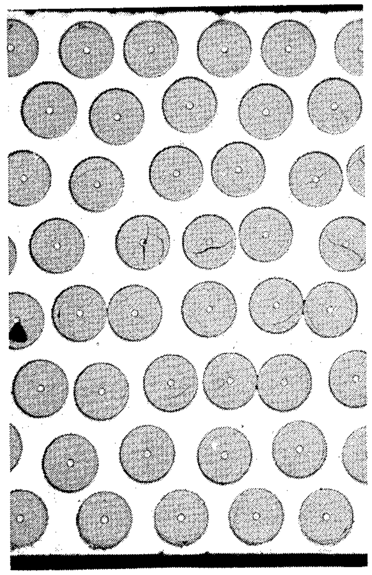


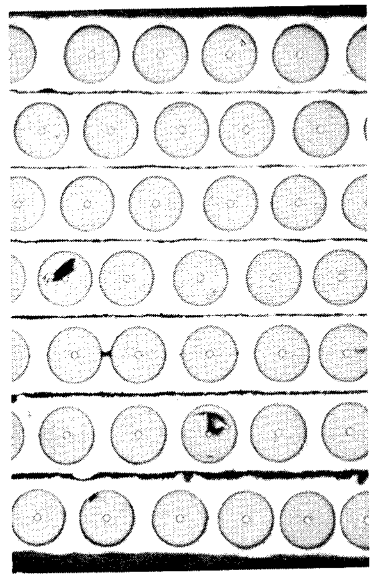
Figure 1. - Schematic of adhesively bonded metal matrix and resin matrix fiber composite hybrid.



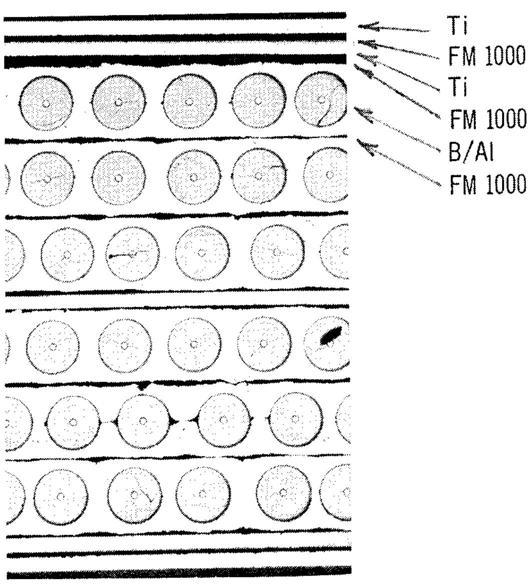
(a) Type I, A-S/E.



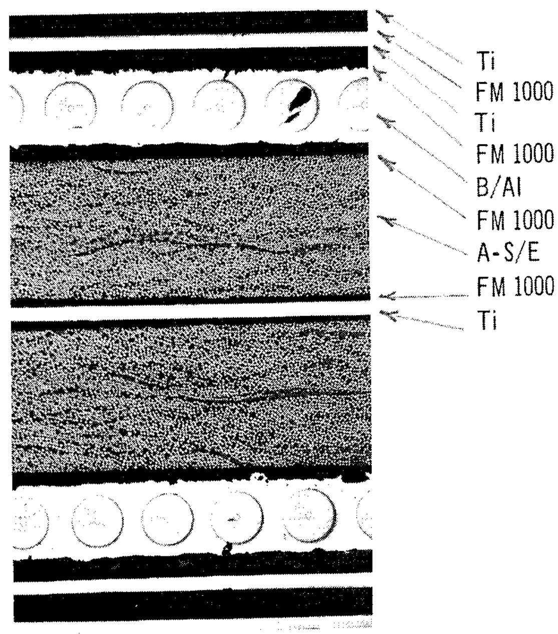
(b) Type II, diffusion bonded B/Al.



(c) Type III, adhesion bonded B/Al.



(d) Type IV, Ti/(B/Al).



(e) Type V, Ti/(B/Al)/(A-S/E).

Figure 2. - Composite specimen cross sections. Magnification, X50.

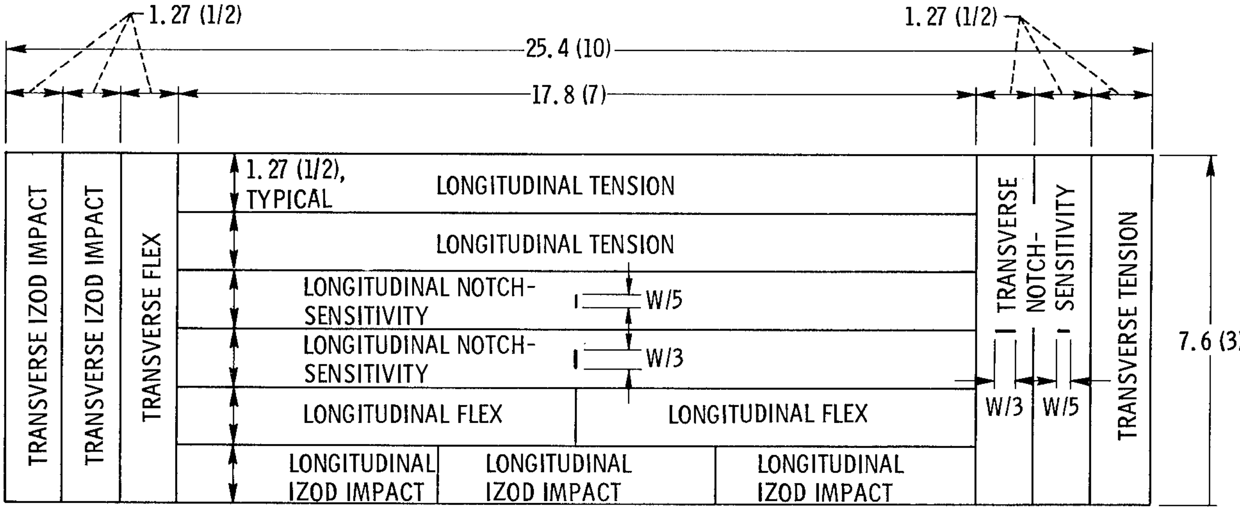


Figure 3. - Typical specimen layout plan. (Nominal values. All dimensions are in cm (in.).)

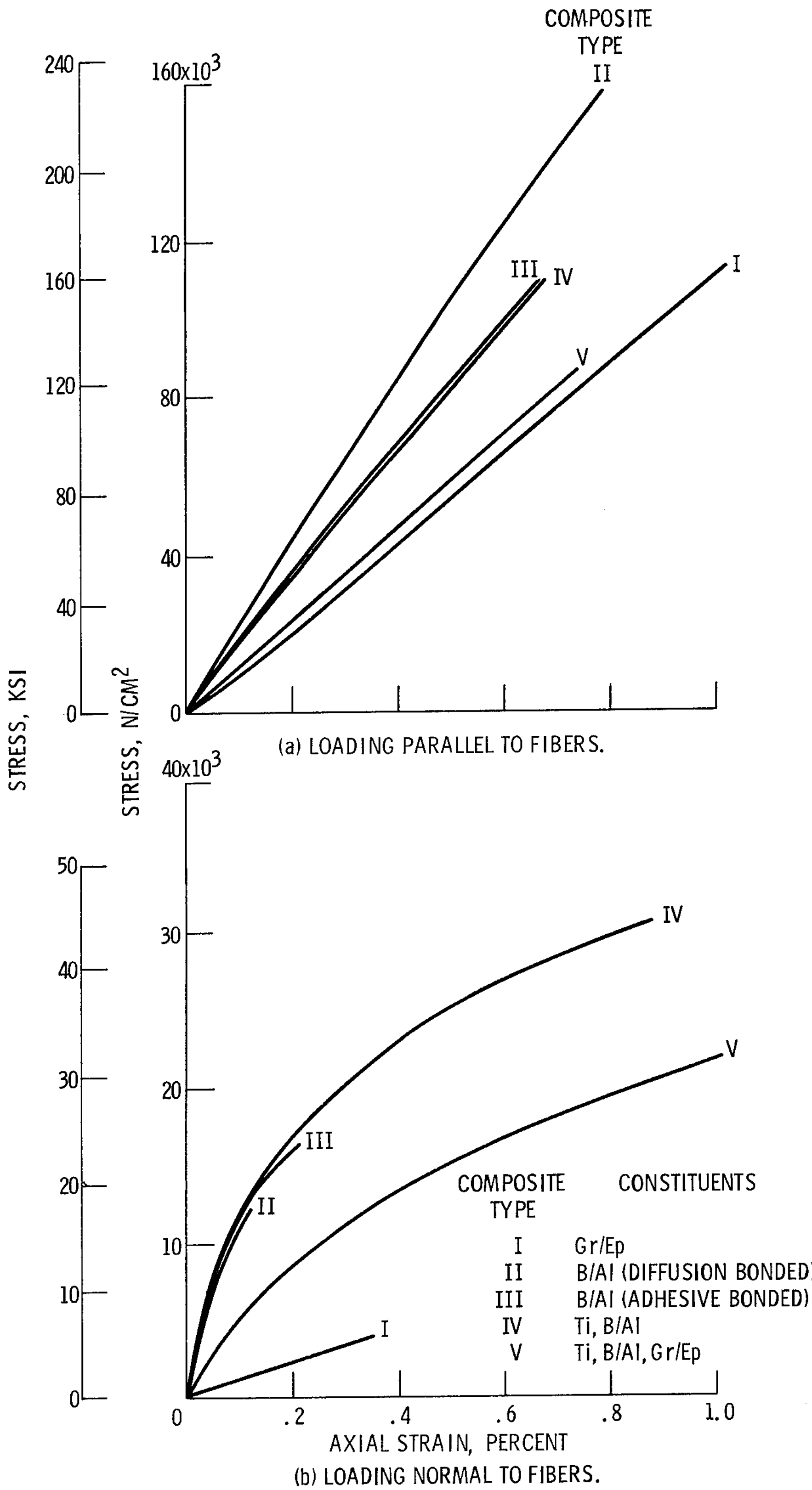


Figure 4. - Stress-strain curves for smooth tensile specimens.

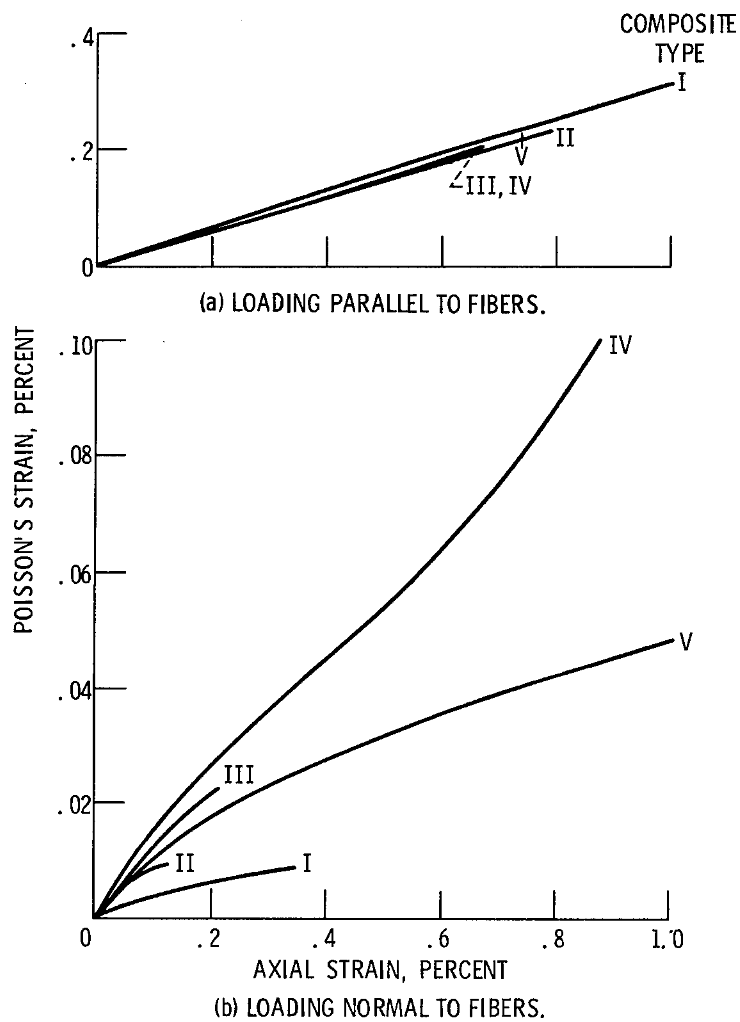
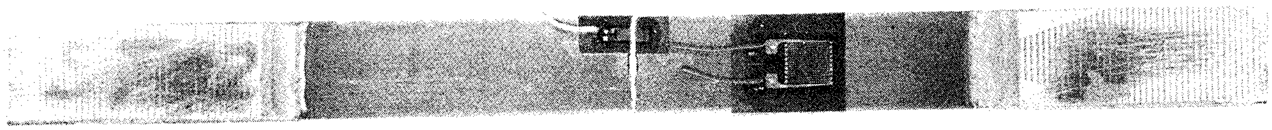
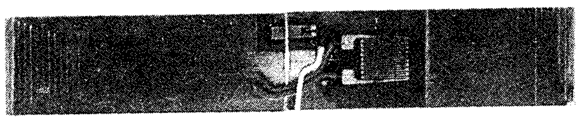


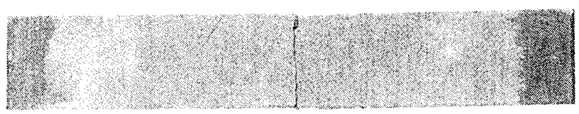
Figure 5. - Poisson's strain for smooth tensile specimens.



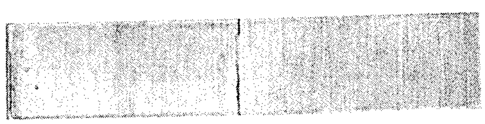
Longitudinal smooth and notch tensile



Transverse smooth and notch tensile

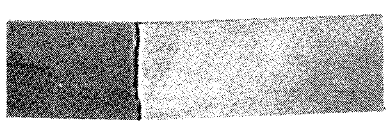


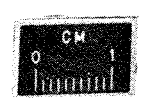
Transverse and longitudinal flexural



Transverse izod impact

C-74-2121





Longitudinal izod impact

Figure 6. - Various fractured composite specimens.

NASA-Langley, 1975 E-8030